U.S. Department of Energy
Energy Efficiency and Renewable Energy

2004 Annual DOE Hydrogen Program Review

Hydrogen Storage

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Outline

- State of the Art
- Barriers/Targets
- Basis for Targets
- Technology Status
- Program Planning/Coordination
- Approach
- 2003 Technical Accomplishments
- Future Plans

The Challenge of Hydrogen Storage – Compact, Lightweight Systems Enabling Greater than 300-Mile Range.

Daimler Sprinter
90mi-26gal-3600psi

Honda FCX
235mi-42gal-5000psi

GM Opel Zafira Minivan
170mi- 26gal- 10,000psi

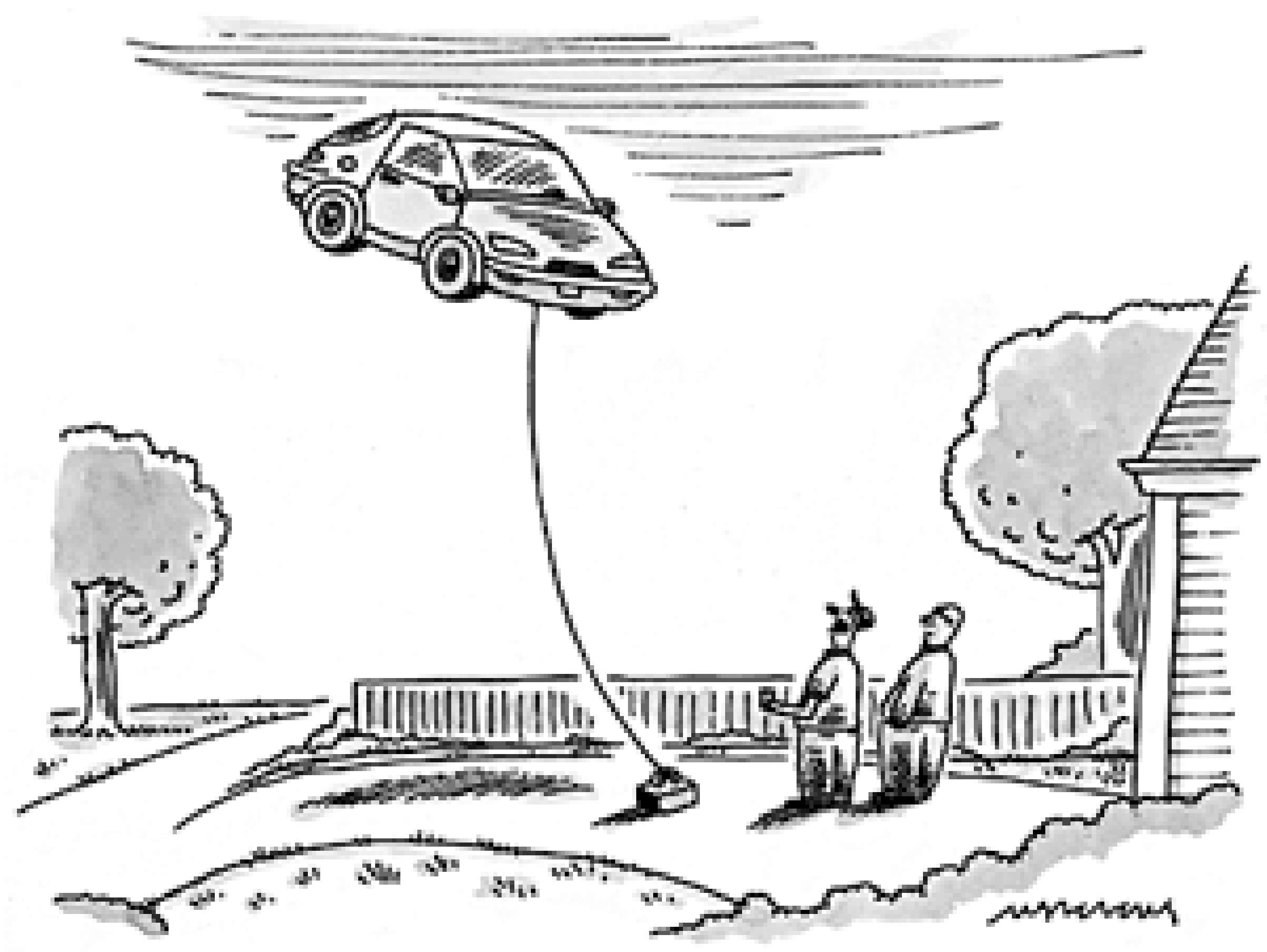
Today's Average Vehicle
370mi-20gal

The State of the Art will help in the near-term, but is impractical for the long-term --- compressed and liquid hydrogen tanks:

- **Will enable vehicle/infrastructure learning demonstrations & initial market penetration**
- **Have limited range & high energy penalty (liquid), preventing full market penetration**
- **Are approaching their weight & volume limits**
- **May have off-board storage applications**

→ DOE R&D focus is on materials-based storage technologies.

Unacceptable Hydrogen Storage Option



"It runs on hydrogen."

On-Board Hydrogen Storage System Barriers/Targets

Main Barriers are Weight, Volume, Cost, and Refueling Time

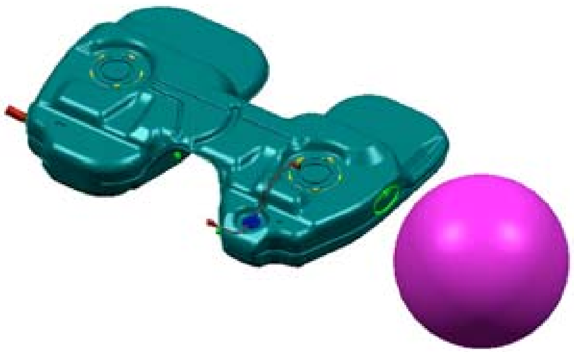
What do these targets mean? For a 5-kg H_2 system…

Storage Parameter	2005	2010	2015
Gravimetric Capacity (Specific energy)	1.5 kWh/kg 0.045 kg H_2/kg	2.0 kWh/kg 0.060 kg H_2/kg	3.0 kWh/kg 0.090 kg H_2/kg
System Weight:	***111 Kg***	***83 Kg***	***55.6 Kg***
Volumetric Capacity (Energy density)	1.2 kWh/L 0.036 kg H_2/L	1.5 kWh/L 0.045 kg H_2/L	2.7 kWh/L 0.081 kg H_2/L
System Volume:	***139 L***	***111 L***	***62 L***
Storage system cost	\$6 /kWh	\$4 /kWh	\$2 /kWh
System Cost:	***\$1000***	***\$666***	***\$333***
Refueling rate	.5 Kg H_2/min	1.5 Kg H_2/min	2.0 Kg H_2/min
Refueling Time:	***10 min***	***3.3 min***	***2.5 min***

Basis for Targets

FreedomCAR On-Board Hydrogen Storage Targets are based on vehicle requirements --- NOT on what storage technologies can achieve.

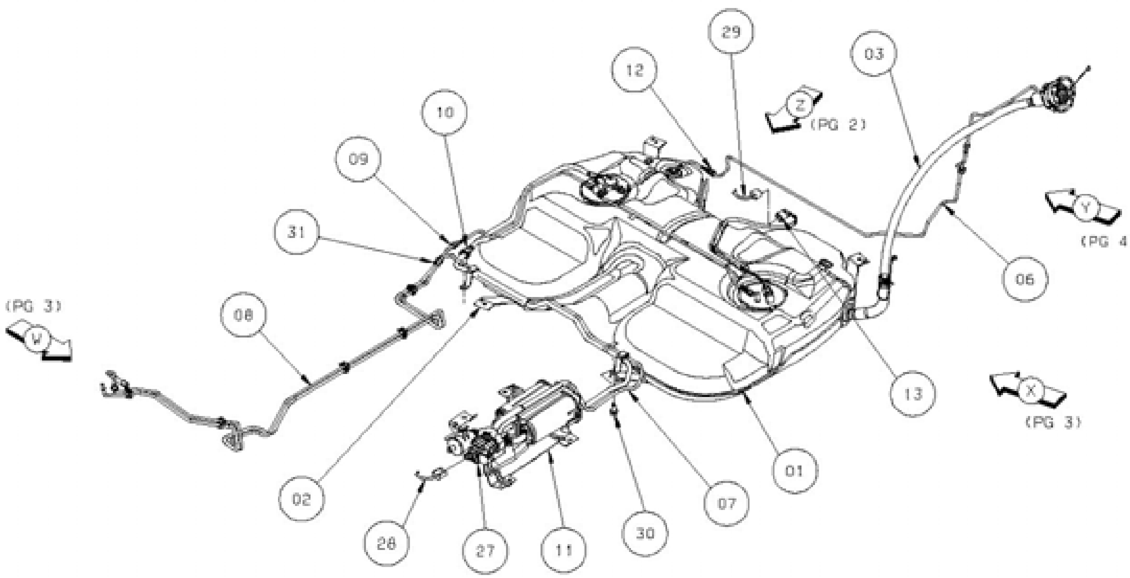
- The baseline is today's vehicles and customer expectations of them, e.g. 370 mile weighted average range
- Fuel economy gains of 2.5X - 3.0X were assumed for fuel cell vehicles
- Today's fuel systems are assumed to include "conformable" components, shaped to fill in available space under the vehicle floorboard and within the chassis
- Some allowance – approximately 20% - can be provided in the capacity targets for fully-conformable storage systems



The Fuel Storage System

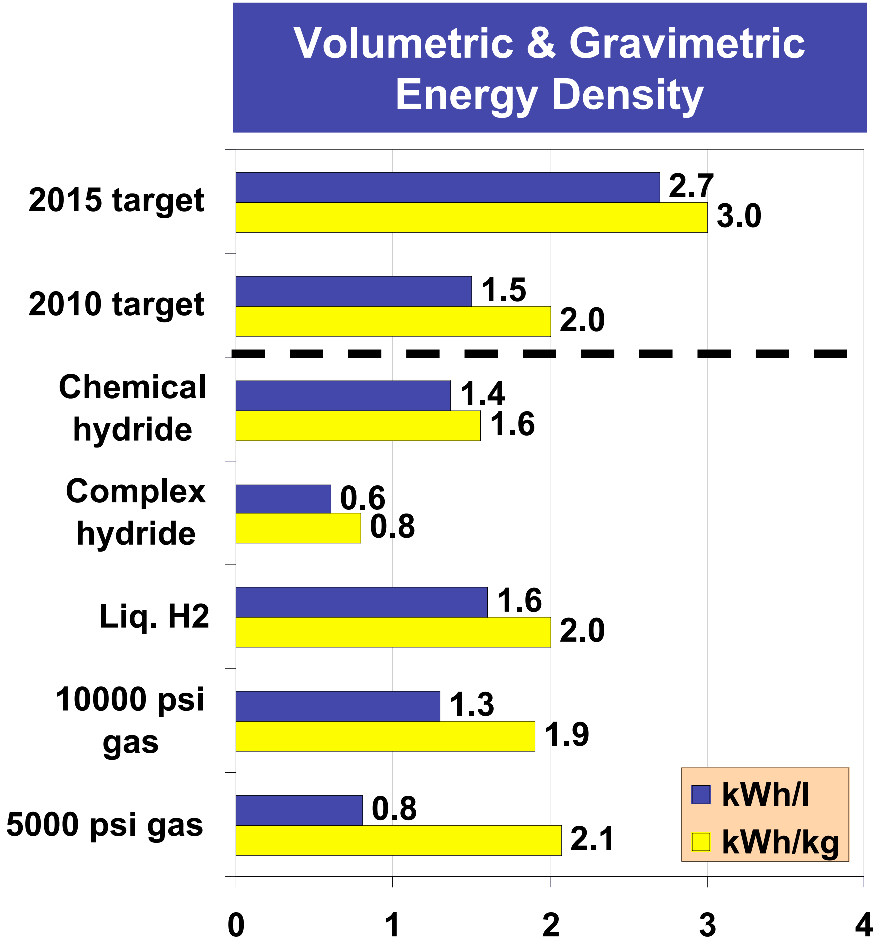
Storage calculations used real volumes and weights of gasoline fuel storage systems in current production vehicles, including:

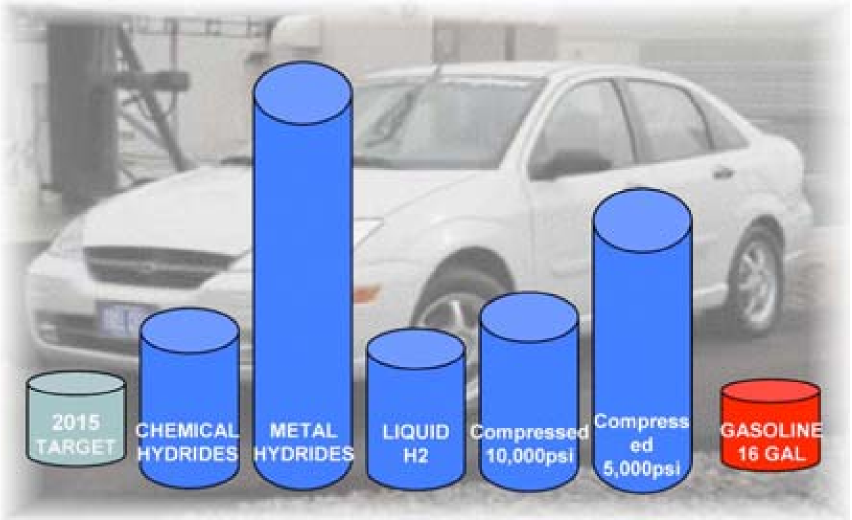
- Fuel tank
- Fuel filler tubes
- Gas cap
- Hoses
- Fuel lines
- Fuel pump
- Fuel filter
- Carbon vapor canister
- Leak detection device
- Purge control solenoid
- Rollover check valve
- Tank hanger straps, clips, & other fasteners



Technology Status - Capacity

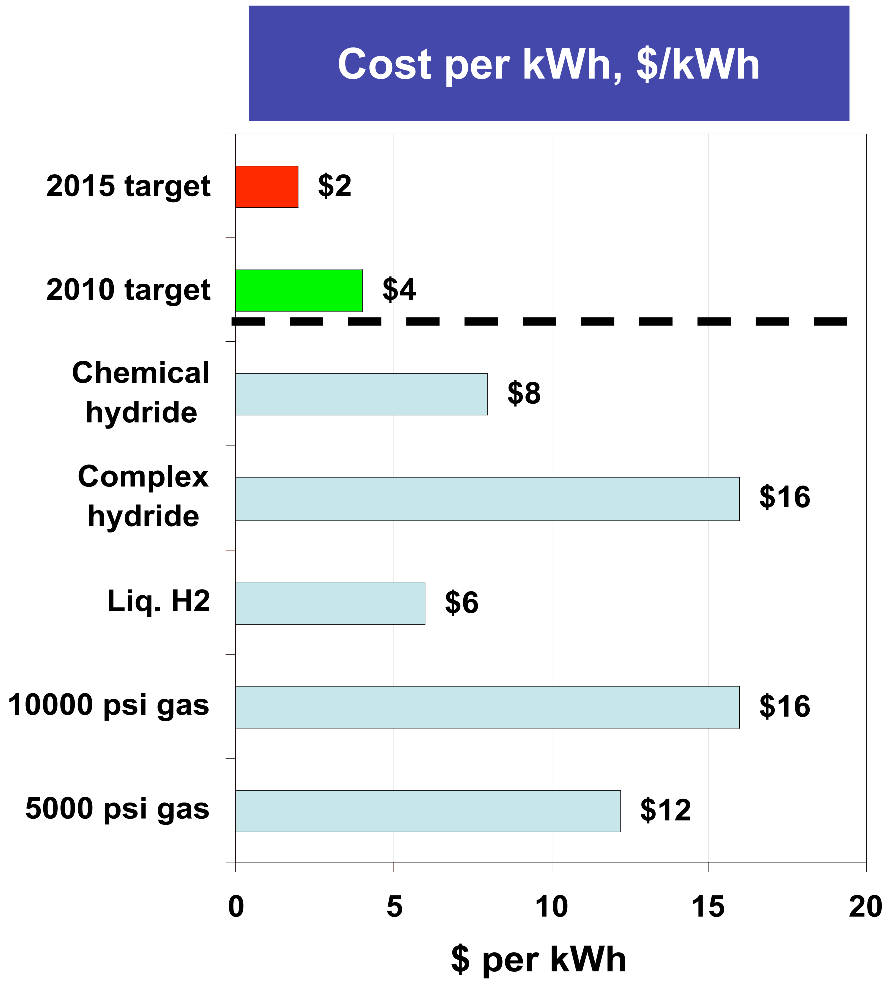
No current H_2 storage technology meets the 2015 targets.





Technology Status – Cost

No current H_2 storage technology meets the cost targets.



For valid comparison, storage system cost must include the cost of the "first charge" so that any "pre-conditioning," i.e. compression, liquefaction, or off-board regeneration cost is considered.

System Issues

Some improvement in system energy density may be achieved by improving the balance of plant.

Storage Approach	Current System Densities (relative to fuel)
Compressed hydrogen	~70%
Liquid hydrogen	~55 - 60%
Solid state	~40 - 50%

Greatest potential for improvement is with solid state systems.

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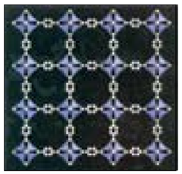
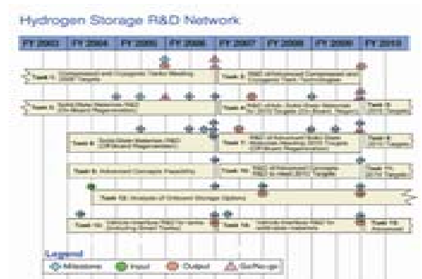
Hydrogen Storage R&D – Planning and Implementing



H_2 Storage Materials Workshop

H_2 Storage "Think Tank"

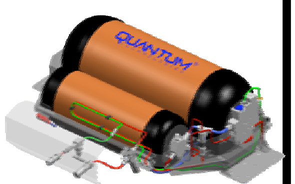


Draft R&D Plan Published

Grand Challenge Issued

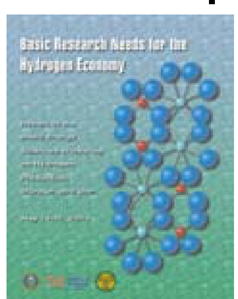
International Conference on Hydrogen Storage Materials
Lucca, Italy

Aug '02 | Oct '02 | Mar '03 | May '03 | Jul '03 | Apr '04 | Jun '05

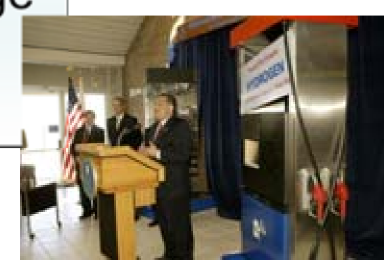


Compressed/Liquid Hydrogen Workshop

Basic Energy Sciences Workshop



Grand Challenge Selections Announced



2004 and 2005 DOE H_2 Storage Projects

Complex Metal Hydrides
SNL Metal Hydride Center
UTRC
UOP
SNL (Livermore)
U. Hawaii

New Materials & Concepts
Cleveland State University
Alfred University
Carnegie Institute
Michigan Tech University
UC Berkeley
UC Santa Barbara
University of Michigan
University of Missouri
University of Connecticut
TOFTEC

Chemical Hydrogen Storage
LANL/PNNL Chem. Hydride Ctr
Millennium Cell
Safe Hydrogen
Air Products
INEEL
Research Triangle Institute

Testing
SwRI

Analysis
TIAX

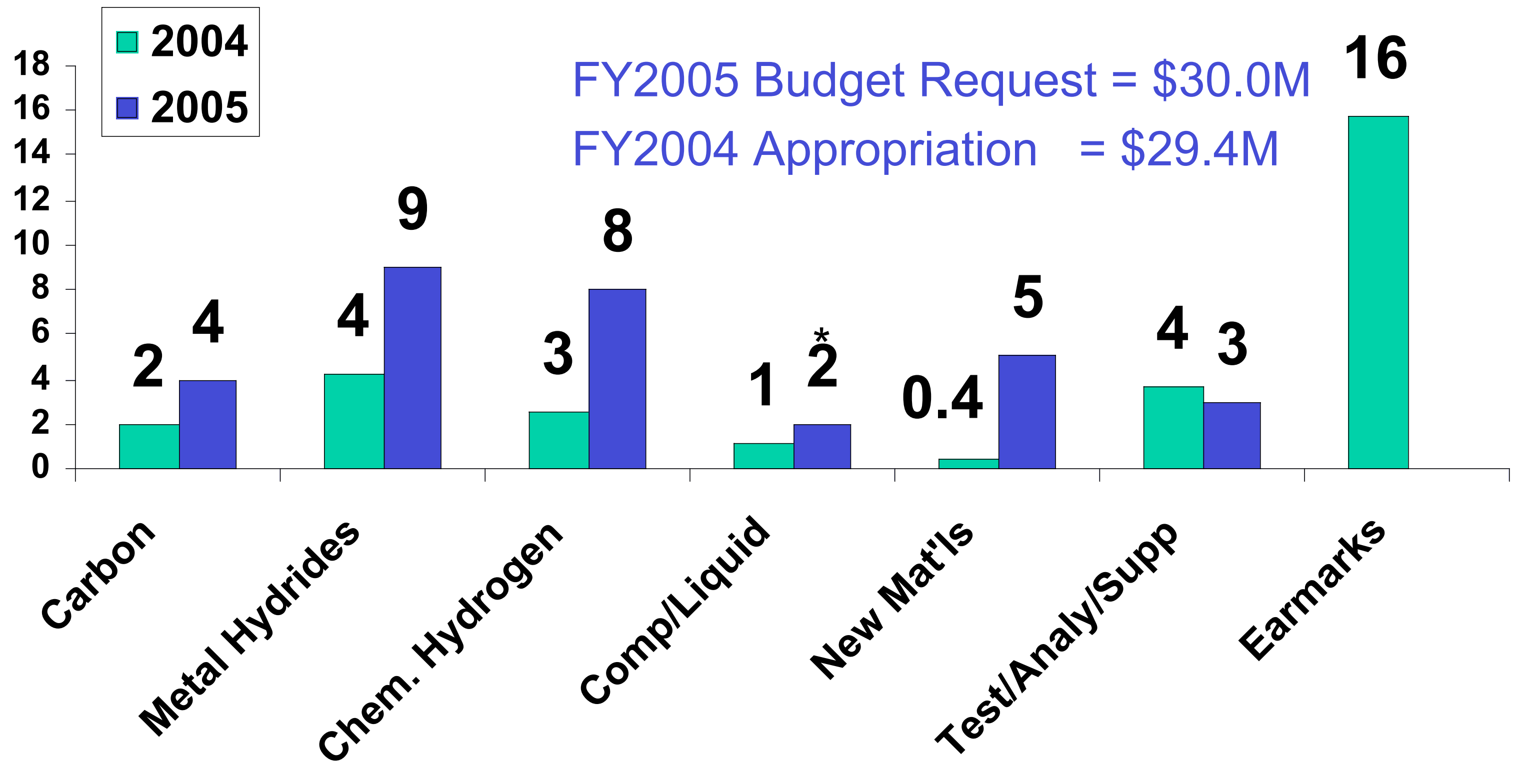
Compressed/ Liquid Tanks
Quantum
LLNL
Gas Technology Institute

Carbon-Based Materials
NREL Carbon-Based Center
University of Pennsylvania
Gas Technology Institute
SUNY - Syracuse

Hydrogen Storage R&D – Funding Distribution

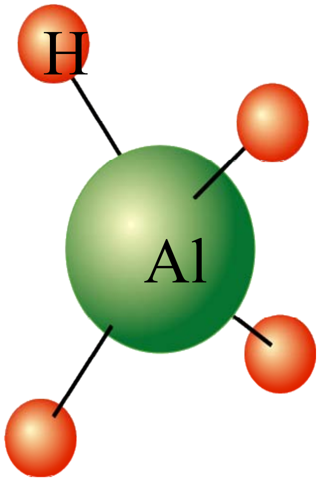
Emphasis: Centers of Excellence and new materials projects to focus on 2010 hydrogen storage goals:

– 2.0 kWh/kg, 1.5 kWh/liter, $4/kWh



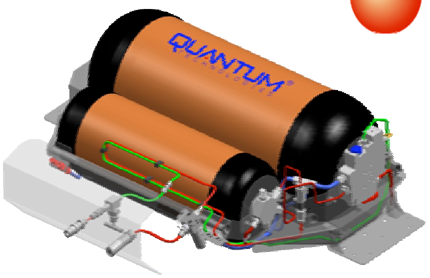
* Focus of compressed and liquid hydrogen R&D is cost reduction and off-board storage.

2003 Technical Accomplishments



- Identified methods to improve kinetics in solid-state materials & pathways to greater capacity (U. Hawaii, SNL)

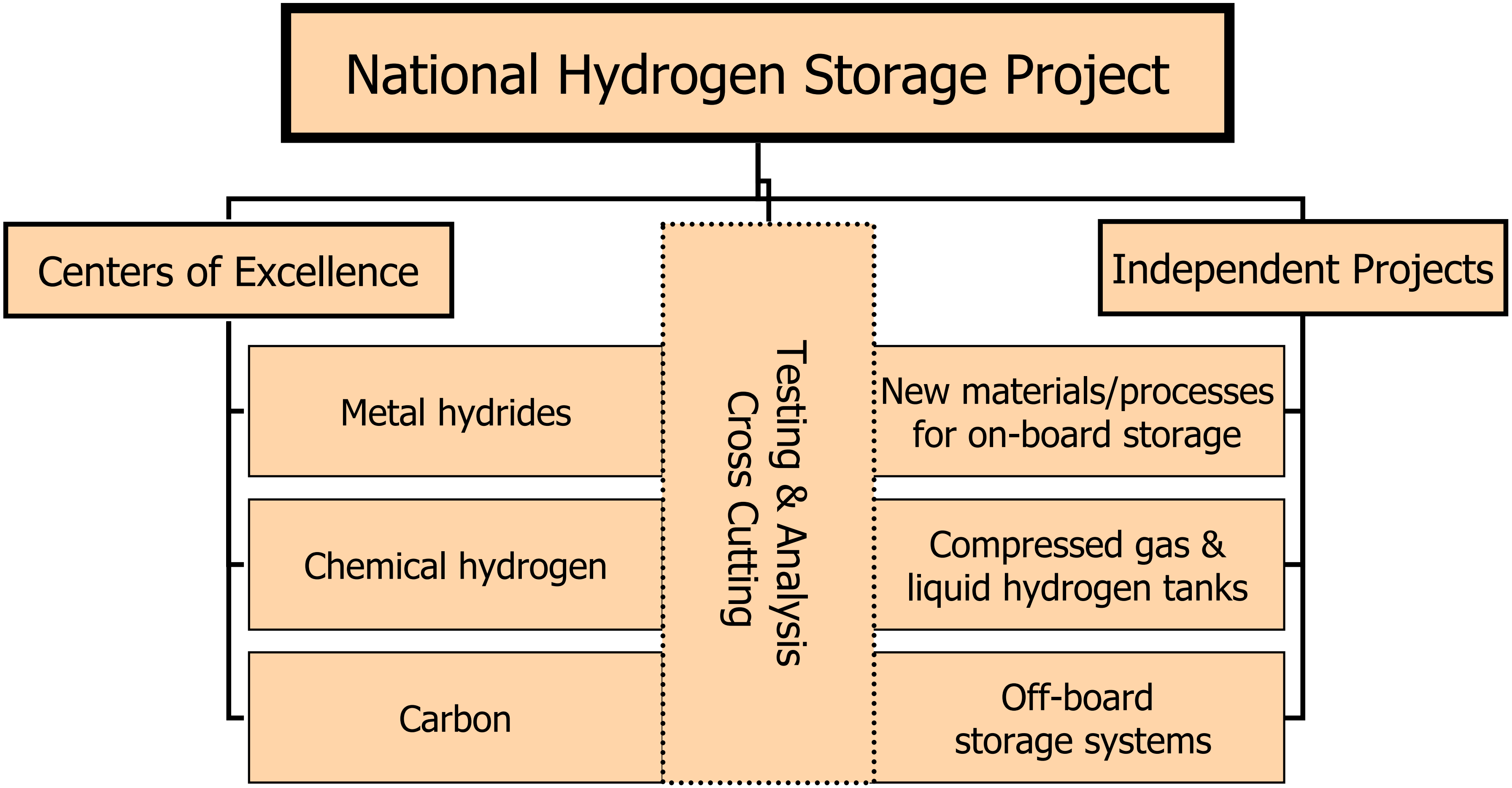
- Demonstrated 10,000-psi tanks with improved energy density, 10X greater cycle life, & fast-fill capability (Quantum)



- Developed and tested novel 5000-psi cryo-compressed tank demonstrating good performance after cryogenic temperature cycling (LLNL)

Future Plans

The DOE "Grand Challenge" will form the basis of the National Hydrogen Storage Project.



Metal Hydride Center of Excellence

Sandia National Laboratory - Livermore

- Light element advanced complex hydrides
- Destabilized binary hydrides
- Intermetallic hydrides
- Lithium amides
- Other reversible hydrides

General Electric	CalTech
Hughes Research Labs	Stanford
Intematix Corp.	Univ. of Hawaii
BNL	Univ. Illinois-UC
JPL	Univ. Nevada-Reno
NIST	Univ. of Pittsburgh
ORNL	University of Utah

Chemical Hydrogen Center of Excellence

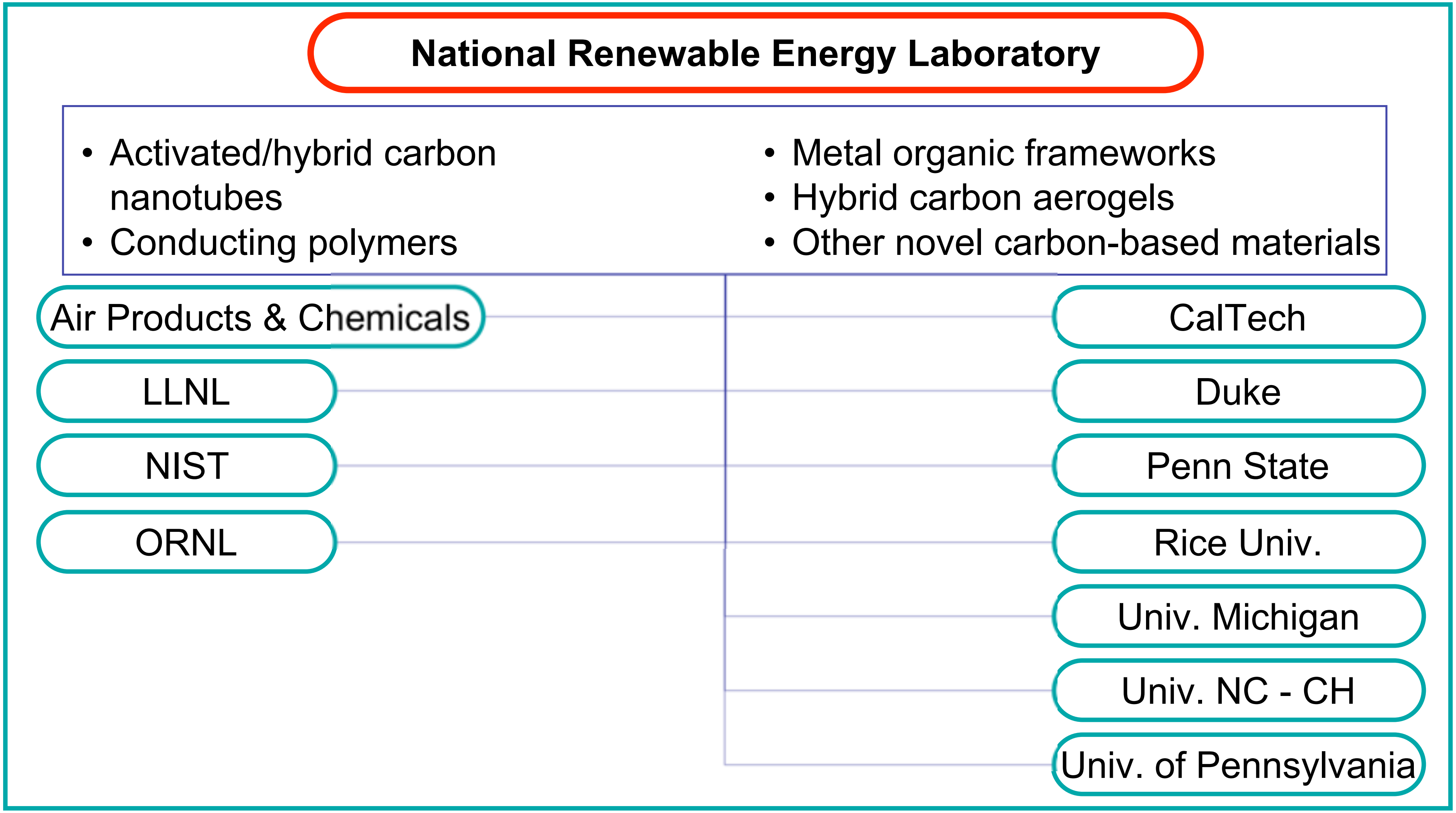
Los Alamos National Laboratory
in partnership with
Pacific Northwest National Laboratory

- Novel boron chemistry (boron hydrides, aminoboranes, polyborane anions)
- Regeneration chemistry & life cycle analysis
- Nanoparticles & light elements

Intematix Corp.
Millennium Cell
Rohm and Haas

Penn State
Univ. Alabama
UC-Davis
UCLA
Univ. of Pennsylvania
Univ. of Washington

Carbon – Based Materials Center of Excellence



Independent Projects

Fourteen independent projects will address new materials and/or processes.

Lead Institution	Area of Research
Alfred University	Glass microspheres – Photo enhanced diffusion
Michigan Technological University	Metal perhydrides
SUNY-Syracuse	Nanostructured activated carbon
UC-Berkeley	Magnesium nanomaterials
UC-Santa Barbara	Organic/inorganic framework materials, metal hydrogen complexes
University of Connecticut	Lithium nitride
University of Michigan	Metal organic frameworks
University of Missouri - St. Louis	Clathrates
University of Pennsylvania	Carbon based nanomaterials- carbide derived carbon
Carnegie Institute	Clathrates
Research Triangle Institute	Amine borane complexes
Gas Technology Institute	Electron charged graphite; Off-Board Storage
TOFTEC, Inc.	Carbon and boron nitride
TIAX LLC	System analysis on fuel chain efficiency, environmental impact and cost

Key Milestones

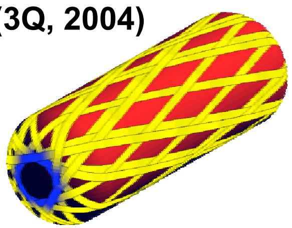
Complete construction of materials test facility (4Q, 2004)

Validate compressed and liquid tanks in complete system achieving 2005 targets (3Q, 2006)

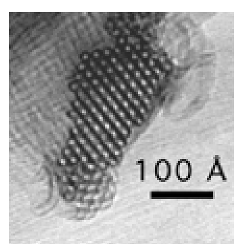
Complete chemical hydride life-cycle analysis (3Q, 2006)

2004 2005 2006 2007

Complete assessment of composite materials and design parameters for 10K psi compressed tank (3Q, 2004)



Demonstrate 4 wt% storage capacity on carbon nanotubes (4Q, 2005)



Down-select from chemical hydrides (4Q, 2006)

Down-select complex hydride materials (4Q, 2006)

Down-select new materials / concepts (4Q, 2006)

Go/no-go decision on carbon nanotubes (4Q, 2006)

For More Information

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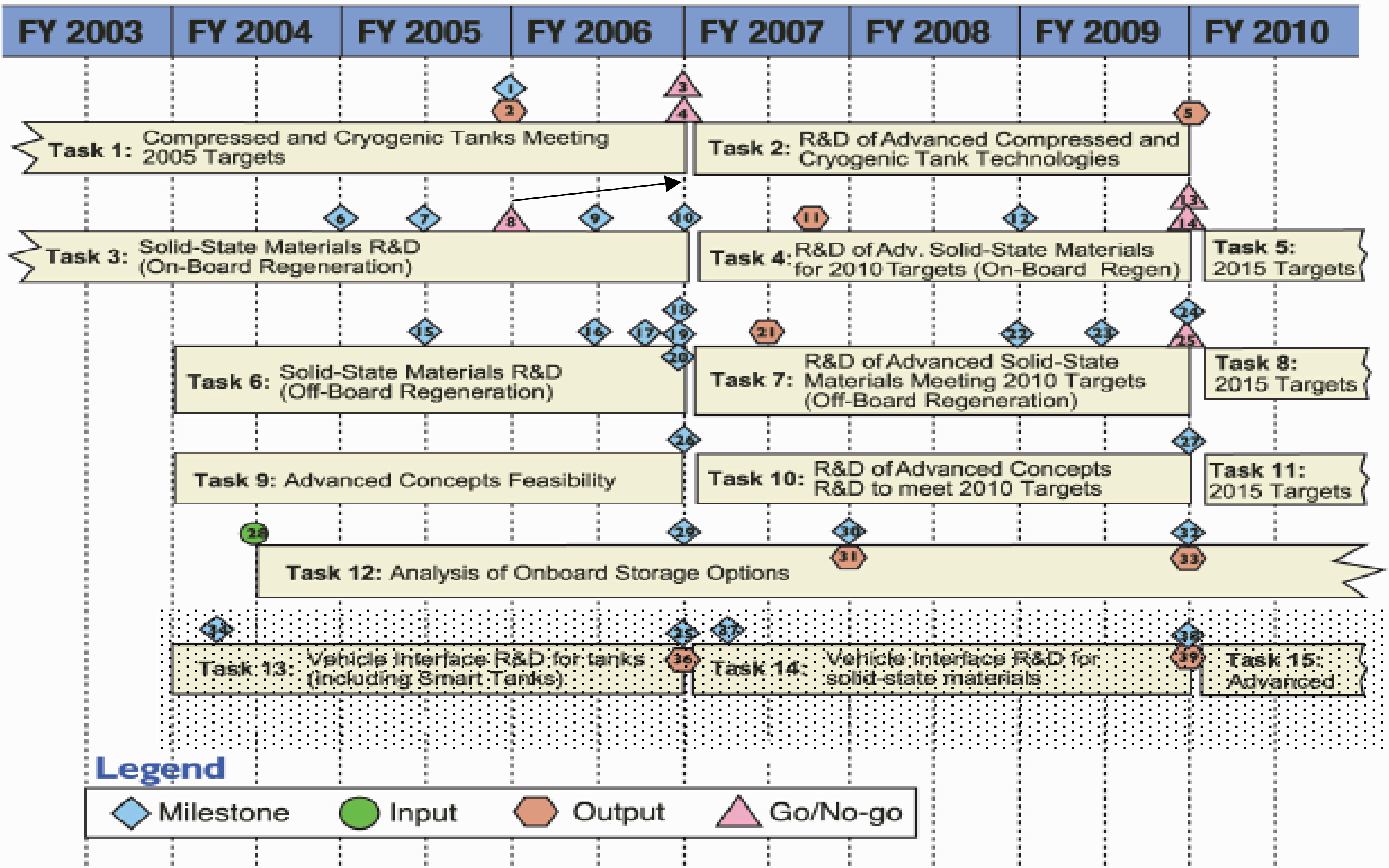
www.eere.energy.gov/hydrogenandfuelcells

Detailed R&D Timeline/Milestones

Hydrogen Storage R&D



Milestones

Compressed/Liquid Tanks

1. Complete feasibility study of hybrid tank concepts (4Q, 2005)
2. **Compressed and cryogenic liquid storage tanks achieving the 2005 targets to Tech Val (3Q, 2006)**
3. Go/no-go decision on insulated pressure vessels for cryogenic tanks with minimum evaporative losses (4Q, 2006)
4. Go/No-Go decision on liquid and compressed tank technologies (4Q, 2006)
5. Advanced compressed/cryo tank technologies to Tech Val (4Q, 2009)

Reversible Solid-State Materials

6. **Complete construction of materials test facility (4Q, 2004)**
7. Complete verification of test facility (2Q, 2005)
8. **Go/no-go decision point on carbon nanotubes (4Q, 2006)** (Reproducibility plan in place)
9. Complete prototype complex hydride integrated system meeting 2005 targets (2Q, 2006)
10. **Downselect complex hydride materials (4Q, 2006)**
11. Complex hydride integrated system meeting 2005 targets (3Q, 2007, to fuel cells and technology validation)
12. Complete prototype complex hydride integrated system meeting 2010 targets (4Q, 2008)
13. Go/no-go decision on continuation of complex hydride R&D (4Q, 2009)
14. Go/no-go decision point on other carbon nanostructures (4Q, 2009)

Chemical Storage

15. Downselect from hydride regeneration processes (2Q, 2005)
16. Demonstrate efficient hydride regeneration laboratory process (2Q, 2006)
17. **Complete chemical hydride life-cycle analysis (3Q, 2006)**
18. Demonstrate scaled-up hydride regeneration process (4Q, 2006)
19. Complete prototype hydride integrated system (4Q, 2006)
20. Downselect from chemical storage approaches for 2010 targets (4Q, 2006)
21. Full-cycle, integrated chemical hydride system meeting 2005 targets (2Q, 2007, to fuel cells and technology validation)
22. Demonstrate advanced hydride regeneration laboratory process (4Q, 2008)
23. Complete prototype advanced chemical storage integrated system (2Q, 2009)
24. Demonstrate scaled-up advanced hydride regeneration process (4Q, 2009)
25. Go/no-go decision point on chemical storage R&D for 2015 targets (4Q, 2009)

Milestones, cont'd

New Materials/Concepts

26. **Downselect from new materials/concepts (4Q, 2006)**
27. Downselect the two most promising new materials/concepts for continued development (4Q, 2009)

Analysis

28. Safety requirements/protocols for onboard storage (3Q, 2004, from safety)
29. Update onboard storage targets (4Q, 2006)
30. Complete analysis of best storage option for 2010 targets (4Q, 2007)
31. Analysis results to delivery (4Q, 2007)
32. Complete analysis of best storage option for 2015 targets (4Q, 2009)
33. Analysis results to delivery (4Q, 2009)